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INFLUENCE OF TEMPORAL INTERVALS ON COMPARATIVE JUDGEMENTS OF PITCH : A STUDY OF SUBJECTIVE RELATIVITY

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INTRODUCTION

The *tau*-effect is a phenomenon first identified by Helson and King (1930) in tactile perception. Suppose three points (p_1, p_2, p_3) are marked off on the subject's forearm, and a tactile stimulus applied to each one in turn. If the interval of time between stimulation of p_2 and p_3 is less than the interval between the stimulation of p_1 and p_2, the distance between p_2 and p_3 seems to the subject less than the distance between P_1 and P_2 although, in fact, the two distances may be the same, or the second distance may be even less than the first. The converse applies if these time relations are reversed. A few years later, Geldreich (1934) demonstrated an analogous effect in visual perception, and subsequently (Cohen *et al.*, 1954) a *tau*-effect was shown to occur in bisections of pitch. However, there was a difference between the procedure employed by Helson and that used in the auditory *tau* experiment. Helson presented two tactile distances (under different temporal conditions) and the subject had to decide which distance was greater. In the auditory *tau* experiment, the subject *himself* decided on the pitch of the intermediate signal, so that he himself determined the two auditory 'distances'. Hence, when he adjusted the second of three tones so that it seemed to him intermediate in pitch between the first and third tones, he made the two tones further apart in frequency when they were presented closer together in time than he did when the time interval between the first and second tones was the same as that between the second and third tones. In commenting on these results Stevens (1957) remarked that the points of bisection that are predicted on the *mel* scale fall within 3 per cent of our observed values.

Our earlier experiments were undertaken to determine whether a binaural *tau*-effect could be established. Our present aim is to discover (a) whether the same effect occurs monaurally; (b) whether there is any difference between the right and left ears in the magnitude of the effect; and (c) whether a difference appears when self-designated right-handed subjects are compared with self-designated left-handed.

PROCEDURE AND SUBJECTS

Our experimental procedure is based on the method employed in studying the visual *kappa*-effect (Cohen *et al.*, 1953) where three successive flashes of light, set horizontally or vertically, delimit two distances; d_1 being the distance between the first and second flashes, and d_2 the distance between the second and third flashes. The subject's task is to adjust the timing of the middle flash so that it seems to him to bisect the temporal interval between the first and third flashes. In the present investigation we replace the flashes by brief tones to delimit the temporal intervals, while a tonal interval, that is, auditory difference between frequencies, is substituted for distance.

The subject, wearing headphones, heard a repeated sequence of three different tones of brief and equal duration. He was asked to adjust the pitch of the second tone so that it appeared to him to be intermediate in pitch between the first and third tones. Each cycle of three tones was repeated after an interval of 5/3 of the total cycle. The two successive time intervals (t_1 and t_2) delimited by the three tones could be varied by the experimenter by adjusting the temporal location of the middle tone in the cycle. Three ratios of t_2/t_1 were employed, namely, 0.5, 1.0 and 2.0, the total interval remaining constant at 1.5 sec. The experimenter set the frequencies of the first and third tones at 1000 Hz and 3000 Hz, or the other way round, depending on whether he was presenting an ascending or a descending order. At the start of each trial, the intermediate frequency was set to a random value between 1000 and 3000 Hz.

Sine-wave tones were generated by three separate oscillators and the frequency of each was monitored by a frequency counter. Under monaural conditions, the subject listened with one ear to the frequencies set by the experimenter, and heard white noise in the other ear. The object of this arrangement was to mask out any cross-over effects which might occur (for example, by bone conduction) and which might prevent the subject's adjustments from being monaural.

There were 72 subjects in all, 36 self-classified as right-and 36 self-classified as left-handed. The dextral and sinistral groups were each divided into three blocks of 12 subjects, one for $t_2/t_1=0.5$, a second for $t_1=t_2$, and a third for $t_2/t_1=2.0$. One half of this block i. e. 6 subjects, made adjustments in the ascending order and the other half in the descending order. Within each block of 6 subjects, the order of adjusting binaurally, with the right ear or with the left ear, was varied, according to the design shown in Table 1, for each subject. Any learning effects which may have occurred are thus distributed over the three listening conditions. Finally, each subject made 10 adjustments, the mean of these being taken for that subject. Thus there were $72\times10\times3$ observatians in all. A representative design for a bock of 6 subjects is shown in Table 1.

Table 1. Experimental design for a representive block of 6 *Ss*
Right-handed; ascending order; $t_2/t_1=0.5$.

	Subject					
	1	2	3	4	5	6
Order of ears	B R L	B L R	R B L	R L B	L B R	L R B

There were twelve such blocks as shown in Table 2.

Table 2. Experimental design: 12 blocks, with six subjects in each*.

t_2/t_1	Order of Presentation			
	Ascending		Descending	
	RH	LH	RH	LH
0.5	RH(A)	LH(A)	RH(D)	LH(D)
1.0	〃	〃	〃	〃
2.0	〃	〃	〃	〃

* RH=right-handed; LH=left-handed;
A=ascending ; D=descending

Results

The experimental results are set out in the four tables, 3 to 6. The *tau*-effect is clearly manifest throughout. In each table, regardless of handedness or of ascending or descending order of frequencies, there is an unmistakable tendency for the tones presented closer in time to be made further apart in frequency, and *vice versa*. For example, the difference between 1491 Hz and 3000 Hz, in Table 3, is greater than that between 1787 Hz and 3000 Hz, which, in turn, exceeds that between 1915 Hz and 3000 Hz. Conversely, in Table 4, the difference between 1968 Hz and 1000 Hz is greater than that between 1522 Hz and 1000 Hz, whilst that between 1230 Hz and 1000 Hz is less than both of them.

An analysis of variance was performed on the data under ascending and descending orders respectively. The results are shown in Table 7 (ascending order) and in Table 8 (descending order). The analysis shows a significant effect of a difference in time ratios, i. e. the *tau*-effect, both in ascending and in descending order. There is no significant ear effect in the descending order, nor any significant interaction between ear and handedness in that order. Consequently, it is difficult to attach much importance to the apparent significance of the ear effect, and of the interaction between ear, handedness and time in the ascending order.

We can bring out the *tau*-effect most clearly, since it appears under all conditions, if we compress Tables 3 and 4 into three values, one for each ratio of t_2 to t_1; and similarly for Tables 5 and 6. These are plotted in Fig. 1. Although there are only three points for plotting each order, the smooth and symmetrical pattern is nevertheless striking.

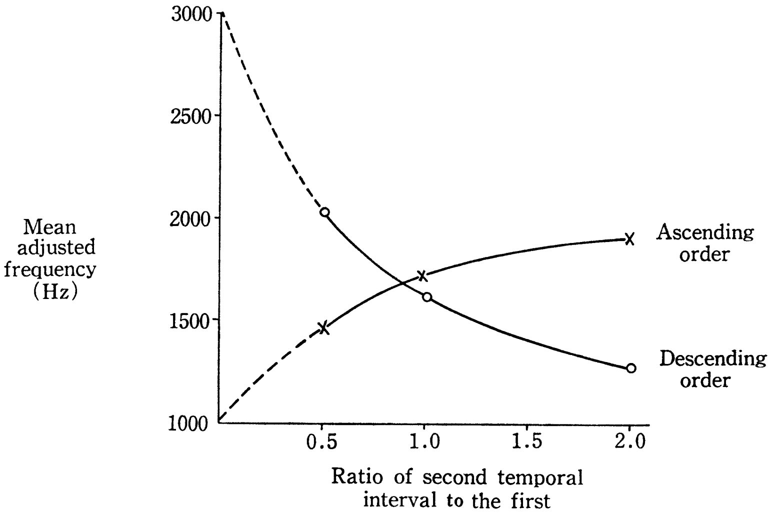

Fig. 1 Mean adjusted frequency (B, R&L) of middle tone in relation to t_2/t_1 (N=36 right-handed+36 left-handed subjects).

Table 3. Auditory *tau*-effect for Tonal Intervals: Mean frequency (and standard deviations) of middle tone from adjustments by right-handed *S*s.
[First tone: 1000 Hz, third tone: 3000 Hz, $T(t_1+t_2)=1.47$ sec*]
RH(A)

N	t_2/t_1	Ears		
		Both	Right	Left
6	0.5	1491 (191)	1357 (151)	1430 (158)
6	1.0	1787 (193)	1758 (134)	1798 (192)
6	2.0	1915 (163)	1951 (104)	1918 (132)

* The duration of the complete cycle was 1.5 sec., of which 0.03 sec was taken up by the onset and decay of the tones necessary to remove clicks. This footnote also applies to Tables 4–6.

Table 4. Auditory *tau*-effect for Tonal Intervals; Mean frequency (and standard deviations) of middle tone from adjustments by right-handed Ss.
[First tone: 3000 Hz, third tone: 1000 Hz, $T(t_1+t_2)=1.47$ sec]
RH(D)

N	t_2/t_1	Ears		
		Both	Right	Left
6	0.5	1968 (221)	2075 (172)	1963 (194)
6	1.0	1522 (210)	1506 (233)	1507 (259)
6	2.0	1230 (153)	1200 (154)	1228 (138)

Table 5. Auditory *tau*-effect for Tonal Intervals: Mean frequency (and standard deviations) of middle tone from adjustments by left-handed *S*s.
[First tone: 1000 Hz, third tone: 3000 Hz, $T(t_1+t_2)=1.47$ sec]
LH(A)

N	t_2/t_1	Ears		
		Both	Right	Left
6	0.5	1486 (94)	1459 (133)	1417 (116)
6	1.0	1759 (174)	1683 (175)	1651 (149)
6	2.0	1923 (97)	1775 (98)	1979 (182)

Table 6. Auditory *tau*-effect for Tonal Intervals: Mean frequency (and standard deviations) of middle tone from adjustments by left-handed *S*s.
[First tone: 3000 Hz, third tone: 1000 Hz, $T(t_1+t_2)=1.47$ sec]
LH(D)

N	t_2/t_1	Ears		
		Both	Right	Left
6	0.5	2056 (227)	2048 (171)	2068 (169)
6	1.0	1730 (181)	1728 (209)	1740 (170)
6	2.0	1292 (146)	1371 (208)	1296 (109)

Table 7. Analysis of variance of results of presentation in the ascending order (First tone: 1000 Hz, third tone: 3000 Hz): see Tables 3 & 5.

Source	*SS*	*df*	*MS*	*F*
Between *S*s				
Handedness(H)	25178	1	25178	
Time(T)	4073823	2	2036911	32.11**
H x T	55792	2	27896	
e(b)	1903100	30	63437	
Within *S*s				
Ear(E)	71467	2	35734	3.71*
E x H	7749	2	3875	
E x T	37995	4	9499	
E x H x T	131524	4	32881	3.42*
e(w)	577664	60	9628	
Total		107		

$^{**}p<0.01$; $^{*}p<0.05$

Table 8. Analysis of variance of results of presentation in the descending order (First tone: 3000 Hz, third tone: 1000 Hz): see Tables 4 & 6.

Source	*SS*	*df*	*MS*	*F*
Between *S*s				
Handedness(H)	387721	1	387721	
Time(T)	10195931	2	5097965	46.50**
H x T	141682	2	70842	
e(b)	3288737	30	109625	
Within *S*s				
Ear(E)	21010	2	10505	
E x H	4050	2	2025	
E x T	17022	4	4255	
E x H x T	34053	4	8513	
e(w)	544026	60	9067	
Total		107		

$^{**}p<0.01$

Since the analysis of variance only shows a significant effect of temporal intervals, for both ascending and descending orders, a more detailed analysis is shown in Table 9 of the overall means regardless of handedness or of ear condition (B, R or L).

In Table 10 we show the t-values by comparing all pairs of temporal conditions, under ascending and descending orders respectively.

Table 9. Means (and standard deviations) of frequency of adjusted second tone for ascending and descending orders, collapsed over handedness and ear condition.

Order	t_2/t_1		
	0.5	1.0	2.0
Ascending	1440 (153)	1739 (185)	1909 (151)
Descending	2030 (202)	1622 (242)	1278 (164)
t	14.0	2.3*	17.0

*$p < 0.05$

Table 10. Values of the t statistic for comparison of pairs of temporal conditions.

Order	0.5 vs. 1.0	0.5 vs. 2.0	1.0 vs. 2.0
Ascending	12.5*	13.1*	4.3*
Descending	7.8*	17.3*	7.1*

*$p < 0.001$

COMPARISON OF JUDGEMENTS FOR UNEQUAL TEMPORAL INTERVALS WITH THOSE FOR EQUAL TEMPORAL INTERVALS

The effect we are investigating may be seen in another light by considering the spread of adjustment values at the different time ratios. This means taking the percentage deviation of judgements for unequal intervals in relation to those for equal intervals. The values for right-handed subjects derived from Tables 3 and 4 are set out in Table 11, and those for left-handed subjects derived from Tables 5 and 6 are set out in Table 12. The pattern of figures in Tables 11 and 12 is similar to that published by Cohen *et al.* (1954) in their Table 2. It will be noted that in Table 11, for right-handed subjects, if we compare the deviations for the right ear with those for the left ear, in three out of four cases the deviation is greater in the right ear. In Table 12, for left-handed subjects, in all four comparisons the deviation is greater in the left ear. Although the differences are small in relation to the standard deviations, there seems nevertheless a tendency for the effect to be associated with handedness. If handedness is governed by the contralateral hemisphere, we may assume that there is also a tendency for this to apply to the *tau*-effect. We arrive at the same conclusion if we examine the percentage deviation from the control condition, $t_1=t_2$, for each of the 48 subjects who made adjustments under conditions of unequal time intervals : 24 of the 72 subjects, it will be recalled, participated only under the control condition. In 31 of the 48 cases, the comparison favours the ipsilateral ear-hand hypothesis so far as the auditory *tau*-effect is concerned. Inspection of Tables 11 and 12 indicates that no overall ear effect is to be expected if the orders were to be combined. Moreover, combining the ascending order values for right- and left-handed indicates why no overall ear effect is to be expected from an analysis of variance of the data under the ascending order.

Table 11. Percentage deviations (and standard deviations) of judgements for unequal when compared with equal temporal intervals* (N=24, right-handed Ss) .

t_2/t_1	Ascending order		Descending order	
	RE	LE	RE	LE
0.5	−22.8 (9.4)	−20.5 (9.6)	37.8 (12.5)	30.3 (14.1)
2.0	11.0 (6.8)	6.7 (8.1)	−17.0 (11.2)	−18.5 (10.0)

*RE=right ear; LE=left ear

Table 12. Percentage deviations (and standard deviations) of judgements for unequal when compared with equal temporal intervals (N=24, left-handed Ss) .

t_2/t_1	Ascending order		Descending order	
	RE	LE	RE	LE
0.5	−13.3 (8.6)	−14.7 (7.7)	18.5 (10.8)	18.8 (10.7)
2.0	5.5 (6.4)	19.9 (12.1)	−20.7 (13.2)	−25.5 (6.9)

We can combine the figures in Table 11 and those in Table 12 so as to eliminate the effects of (a) order of presentation of time intervals and (b) ascending and descending order of frequency. We then obtain mean deviations ranging from 15 per cent for LH (right ear) to 23 per cent for RH (right ear). The mean deviation at

17 or 18 per cent is much the same for right-handed and left-handed subjects when both ears are employed; and it is also much the same in both cases at 19 or 20 per cent when the left ear is employed.

THE PROBLEM OF HYSTERESIS

In Stevens' paper (1957) cited above, the author notes that a subject may adjust a stimulus to a higher value in an ascending order than in a descending order; this he called a *hysteresis* (or 'lagging behind') effect. He claimed that this effect appears in experiments on bisection and equisection, but only in those sensory continua which he describes as 'additive', not in those which he describes as 'substitutive'. If this is true, the hysteresis effect should occur, for example, in bisections of loudness but not in bisections of pitch. He observed that, in our previous experiments, when $t_1=t_2$ the hysteresis effect was statistically negligible, when the delimiting tones were 1000 and 3000 Hz, and that when the delimiting tones were 2000 and 4000 Hz, the value for the descending order was higher than for the ascending, though not significantly so.

In our present experiments, when $t_1=t_2$, there is a slight hysteresis effect, barely exceeding one standard deviation, in the right-handed subjects, but none in the left-handed subjects. When all the data are collapsed over handedness and ear conditions, as in Table 9, the hysteresis effect reaches the 5 per cent level of significance. When $t_1 \neq t_2$ substantial differences between the ascending and descending orders appear which are, of course, manifestations of the *tau*-effect. Nevertheless, some uncertainty about the genuineness of the hysteresis effect, under our experimental conditions, must remain.

Discussion

The phenomenon we are confronted with is that of a bias in the bisection of a tonal interval which is a function of the time relations involved. We must leave open the question whether the bias is to be regarded as an 'error' or whether it is, in some unknown fashion, a biologically advantageous feature. We must also leave open the question whether the class of phenomena exemplified by the *tau*-effect differs in principle from the class of psychological effects known as 'illusions'. we shall limit ourselves to the problem of the bias as such. The heart of the matter is that when the intermediate tone is presented closer in time to the third tone than to the first tone, it is assigned a frequency further from the third tone than the one assigned to it when $t_1=t_2$. In the ascending order, when $t_2<t_1$, the intermediate tone is assigned a lower frequency than the one it receives when $t_1=t_2$. In the descending order, it is assigned a higher frequency. That is to say, in the former case the

'distance' or interval between the intermediate tone and the terminal tone of 3000 Hz is too great, while in the latter case the 'distance' between the intermediate tone and the terminal tone of 1000 Hz is too great. These relations are necessarily reversed when the intermediate tone is presented closer in time to the first than to the third tone, because the judgements made are always comparative, i. e. the subject compares two tonal intervals.

This state of affairs might be looked at in the light of the following consideration. If two tones are placed too close together in time, discrimination between them is feeble and the subject may be tempted to place them too far apart in terms of frequency. If, on the other hand, they are presented further apart in time than the optimal interval, the subject may be tempted to place them too close together. This, however, is more of a description than an explanation.

The experimenter instructs the subject to seek a reference value, namely, the mid-point between the two terminal frequencies. It is left to the subject to locate this reference value. This is only possible by holding the third tone focally in consciousness while comparing it with the marginally held fading impression of the first tone. This is not an easy task to perform, judging by the subject's lack of confidence in the accuracy of his adjustment. And his task is rendered still more difficult by the fact that the time relations of the tones are unequal. It is as though, without the subject's knowledge, when, for example, $t_2<t_1$, some force were constraining him to place the intermediate tone further from the third tone than he would place it if $t_1=t_2$. He is unaware of his own bias, much as though someone had, without his noticing it, slipped a heavy stone into a suitcase he was carrying.

The experimenter's instructions only provide a guide to the subject in seeking his criterion or reference value viz. what seems to him the mid-point of the tonal interval. In making his adjustment (repeated in 10 trials) he oscillates for some time before reaching his decision. His pitch discrimination capacity, together with his tonal sensitivity, enables him unwittingly to assess his error and react to it. His tentative adjustments constitute his output responding to the input signals – the two terminal frequencies. And the discrepancy, which he senses between his tentative adjustments and his inner norm or reference value, constitutes the negative feedback which guides his control towards his target.

Any adequate attempt to account for the auditory *tau*-effect must, however, place it in the context of the entire range of *kappa*-and *tau*-effects, including the *kappa-tau* and the *kappa*-movent effects, in the visual, auditory, tactile and kinaesthetic modalities. A 'high level' explanation is required, and any lower level explanation, that pertains to a local or specific phenomenon must be compatible with, and capable of being subsumed under a more general model. Such a 'high level' model can, at this stage, only be suggested in the most tentative fashion, since so much of the neurophysiological basis of the various effects remains obscunre. An eventual explanation, we suggest, may perhaps be couched in terms of a hierarchical order of perceptual processes into which temporal and/or spatial factors enter as an integral component. The *hierarchical* character of the proposed model seems implied by the nature of the integration of sensory elements, resulting from the experimenter's signals, in a complex act of judgement.

There is one further point. It would seem that the temporal constituent of perceptual processes is the most pervasive feature of experience. All our sensations, feelings and thoughts are felt to have duration. Psychological time is accordingly the basic currency of experience, and there is ample evidence that a trade-off occurs between time and distance, on the one hand, and between time and velocity, on the other. These relations appear under the various *kappa*-, *kappa-tau*, and *kappa*-movement effects. There is a demonstrable interdependence between time, distance and movement, whether the movement is experienced passively by the driver of a vehicle (or by his passenger) or whether it is the observed movement of a target in a visual display. Time may also be traded off with intensity, for signals may be integrated over time. Thus a weaker signal may be equated with a more intense one if the duration of the former exceeds that of the latter by a given amount: ten years in Purgatory may be exchanged for one year in the Inferno! In the present experiments, we have shown, by comparing the results for unequal time intervals with those when $t_1=t_2$, that a temporal element probably enters into such a trade-off partnership in the perception of auditory pitch: the bisection of a tonal interval is a function of its temporal components.

Several issues of indirect interest arise from the experiments that may have a bearing on signal detection theory and decision theory. The initial value recorded for each subject was the mean of 10 trials under each ear and time condition. An analysis of the considerable amount of information yielded by these trials was not germane for the present purpose, though we intend to undertake it in the future. Thus there is, first, the question of the number of repetition of cycles (i.e. 1000 Hz to 3000 Hz or *vice versa*) each subject felt he needed to hear before making his final adjustment in each trial. Did the number of cycles decline with successive trials? Second, there is the question of the subject's total decision time. How was this affected by successive trials? Third, there is the question of the effect of making the intermediate frequency *below* the arithmetic mean frequency (i.e. 2000 Hz) or *above* it, before the subject makes his adjustment. Fourthly, there is the question of the degree of confidence the subject places in the precision of his adjustment. It would seem that most subjects, after making every effort to locate the intermediate frequency at what seems to them to be the point of bisection, nevertheless feel uncertain about the accuracy of their judgement. In a subsequent experiment, we hope to mesure this confidence. If it is confirmed that the degree of confidence is generally low, it would seem to follow that a consistent *tau*-effect can occur even if the subject is not consciously confident as to the success of his effort. No knowledge of results was given to the subjects, and the nature of the experiment is such as to make it unlikely that knowledge of results would have led to different results. More generally, it would appear that consistent patterns of perceptual judgements and decisions are possible even if the subject is not conscious of the accuracy of his performance.

Finally, returning to the three questions we raised in the Introduction and dealing with the third question before the second, we conclude that (a) the *tau*-effect occurs monaurally as well as binaurally; (b) in right-handed subjects, the effect is rather more marked in the right ear, and in left-handed subjects it is more marked in the left ear; (c) in the light of the analysis in terms of percentage deviations, together with (d), if we disregard handedness, there appears to be no overall ear effect.

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Zusammenfassung

Experimente sind durchgefuhrt worden, welche beweisen, dass der auditorische *tau*-Effekt sowohl monaural als auch binaural stattfindet. Der Effekt besteht darin, dass die Versuchsperson, welche es unternimmt, die Distanz zwischen zwei Tonfrequenzen zu halbieren, systematisch von den angewendeten zeitlichen Beziehungen beeinflusst wird.

Nehmen wir an, dass t_1 die Zeitdauer zwischen der ersten und der zweiten, t_2 diejenige zwischen der zweiten und der dritten Frequenz, darstellt. Wenn die Proportion $t_2/t_1 \neq 1.0$, wird die Halbierung systematisch verzerrt. Die Tondistanz zweier Frequenzen, welche Kurz hintereinander präsentiert werden, muss grösser sein als diejenige zweier Frequenzen, zwischen welchen eine längere Zeitdauer liegt, damit der Unterschied zwischen dem ersten Paar von Frequenzen phänomenal dem des zweiten Paares gleichkommt.

72 Versuchspersonen, 50% männliche und 50% weibliche, haben an dem Experiment teilgenommen. Im Allgemeinen scheint nichts auf einen Unterschied zwischen der rechtshändigen und der linkshändigen Gruppe hinzuweisen. Gewisse Resultate deutenjedoch darauf hin, dass in der rechtshändigen Gruppe der Effekt des rechten, in der linkshändigen derjenige des linken Ohres grösser ist.

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